Data, Site, and Network Requirements for GPS-based Sensing of Precipitable Water Vapor

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INTRODUCTION

The size and scope of permanent arrays of continuously operating GPS receivers will soon rival the current worldwide network of approximately 600 radiosonde launch sites, The accuracy of ground-based GPS estimates of precipitable water vapor (PWV) has already been demonstrated through a number of direct comparisons with simultaneous radiosonde and water vapor radiometer (WVR) measurements of this quantity (NOAA, 1995). A GPS-based system for determination of PWV offers the added benefits of more frequent estimates of this quantity and the potential for near real time availability. Including additional PWV estimates into numerical weather models could significantly improve the accuracy of weather forecasts.

We describe here the components of a GPS-based system that is capable of providing near real time estimates of PWV. These include:

- A surface meteorological instrument package capable of providing accurate measurements of barometric pressure and surface temperature. Ideally, this instrument package should be interfaced directly to a GPS receiver, and incorporate the pressure and temperature data directly into the GPS data stream.

- A means of transferring both the GPS and surface nw.te.orological data to a central processing facility in near real time.

- A source of, or a means of computing, GPS orbits of sufficient accuracy whenever new data arrive at the central processing facility.

- An automated data handling and analysis system that can produce estimates of PWV from the GPS and surface meteorological data and GPS orbits whenever new data from a remote site arrive at the central processing facility.

in the remainder of this paper we describe each of these requirements in some detail and present the results of tests that have been performed as part of our effort to develop a prototype ground-based system for estimation of PWV using the GPS.

ESTIMATION OF PWV USING THE GPS

The use of GPS data to estimate precipitable water vapor has been discussed in detail by others (Bevis, 1992; Bevis, 1994; Rocken, 1993). In summary, the effect of the atmosphere on the transmission of GPS signals is modeled as a single zenith "delay" parameter. The equivalent delay at other elevation angles is determined by a mapping function that is roughly proportional to the inverse of the sine of the elevation angle.. This total zenith delay is modeled as the sum of a hydrostatic, or "dry" delay, due to the induced dipole effects of all atmospheric gases, and a "wet" delay clue to the permanent dipole effect of atmospheric water vapor. Hence,

$$\tau_{GPS} = \tau_D + \tau_W \tag{1}$$

where τ_{GPS} is the total zenith delay estimated from the GPS data, τ_D is the zenith dry delay, and τ_W is the zenith wet delay.

To a high degree of accuracy, the dry delay can be computed independently using the surface barometric pressure and the relation (Davis, 1985):

$$\tau_D = 0.22768(1 - .00266 \cos[2\phi] - .00028 h_o)^{-1} P_o \tag{2}$$

where τ_D is the dry delay (cm), h_o is the height (km) of the pressure sensor above the geoid, P_o is the surface pressure (mbar), and ϕ is the latitude of the observing site.. Thus, by combining estimates of τ_{GPS} obtained from processing GPS data, and estimates of τ_D from simultaneous surface pressure measurements, it is possible, using Eqs. (1) and (2), to obtain estimates of the wet delay, τ_W.

The zenith wet delays, τ_W, at each measurement time are related to the precipitable water, PW, by (Bevis, 1994):

$$Pw \approx \Pi \tau_w \qquad (3)$$

where Π is a temperature dependent constant (- 1/6). Π is related to the refractivity coefficients of water vapor by

$$\Pi = \frac{10'}{R_w \rho_w \left((k_3/T_m) + k_2 \cdot \text{ink}, \right)} \qquad (4)$$

where $k_1, k_2,$ and k_3 are the refractivity coefficients for water (Smith, 1953), m is M_w/M_d, the ratio of the molar masses of water vapor and dry air, R_w is the gas constant of water vapor, ρ_w is the mass density of liquid water, and T_m is the average temperature of the atmosphere over the receiver. T_m can be expressed as (Davis, 1985)

$$T_m = \frac{\int (P_v/T) dz}{\int (P_v/T^2) dz} \qquad (5)$$

where P_v is the partial pressure of water vapor, T is the temperature in Kelvins and the integrals are taken over the vertical coordinate, z.

An empirical relationship between the surface temperature measured at the receiver and T_m has been established by analysis of data from a large number of radiosonde launches throughout the United States. Thus it is possible to estimate T_m from the measured surface temperature T_s using

$$T_m = 70.2 + 0.72 T_s \qquad (6)$$

The accuracy of the average temperatures computed using Eq. (6) is estimated to be approximately 1-2% (Bevis, 1992).

COMPARISON WITH WVR MEASUREMENTS

One means of establishing the accuracy of GPS-based estimates of PWV is to compare them with those obtained from a well established technique such as a water vapor radiometry, lidar, or direct radiosonde measurements of water vapor. In this section we present the results of a comparison of GPS-based estimates of PWV with those obtained from a collocated water vapor radiometer.

The GPS data used in the WVR comparison were obtained from an 8 channel, dual frequency, TurboRogue SNR 8000™ GPS receiver that is in continuous operation at a site located at the Jet Propulsion laboratory, Pasadena, CA. Simultaneous surface pressure and temperature measurements were obtained from a Paroscientific Model 601611 pressure sensor with a stated accuracy of 0.01 % of the nominal atmospheric pressure at the comparison silt. Surface temperatures were obtained from the temperature sensor contained within the pressure sensor.

The water vapor radiometer used in this comparison was a 3-channel design developed at JPL (Keihm, 1991). During the period of the intercomparison, the WVR operated continuously in a fixed scanning pattern. Measurements of the sky brightness temperature were made at a number of elevation angles to allow necessary gain corrections to be made to the WVR signal. PWV estimates used in this comparison were obtained from the WVR measurements made at zenith.

GPS-based estimates of PWV were obtained by processing the data with the GIPSY/OASIS 11 software system developed at JPL (Lichten, 1987; Severs, 1990). Precise GPS orbits, obtained using data from a global network of GPS receivers, were used in estimation of the total zenith tropospheric delays. Data from elevation angles as low as 7.0° were processed to estimate the total zenith tropospheric delays from the GPS data at the JPL site..

Figure 1 shows typical results for 3 days of WVR and GPS-based estimates of PWV. This figure also illustrates the effect of including observations at low elevation angles when estimating PWV from GPS data. In routine processing of GPS data for geodetic purposes, these observations are often discarded to mitigate the effects of increased multipath at lower elevation angles. However, it is apparent from the results shown in Fig. 1 that including observations at low elevation angles improves the agreement with the WVR measurements of PWV at this site.

This effect is also evident in mean values of the PWV differences shown in Table 1. These results clearly indicate that including observations at lower elevation angles improves the agreement between the GPS and WVR estimates of PWV. This improvement is thought to result from breaking the high degree of correlation between the total zenith delay and the local vertical position of the GPS station location, both of which are estimated when the GPS data are processed. The sensitivity of these parameters to GPS data is nearly the same at higher elevation angles, and only begins to show significant differences at low elevation angles. To take advantage of these differences and obtain accurate estimates of the total zenith delay, it may prove necessary to include GPS

TABLE 1 Summary of GPS & PWV differences

Dates	Min. Elev.[a]	No. points	Mean diff., mm	RMS diff., mm
8/11- 8/28[b]	15°	1032	2.47 ± 1.05	2.69
8/11- 8/28[b]	7°	1113	0,912 1.03	1.38
9/29 - 10/27[c]	15°	1669	1.69 ±1.02	1.98
9/29 - 10127[c]	7°	1669	-0.07 ±1.07	1.07

[a] Lowest elevation angle allowed for GPS observations.
[b] Average PWV for this period: 19.05 mm.
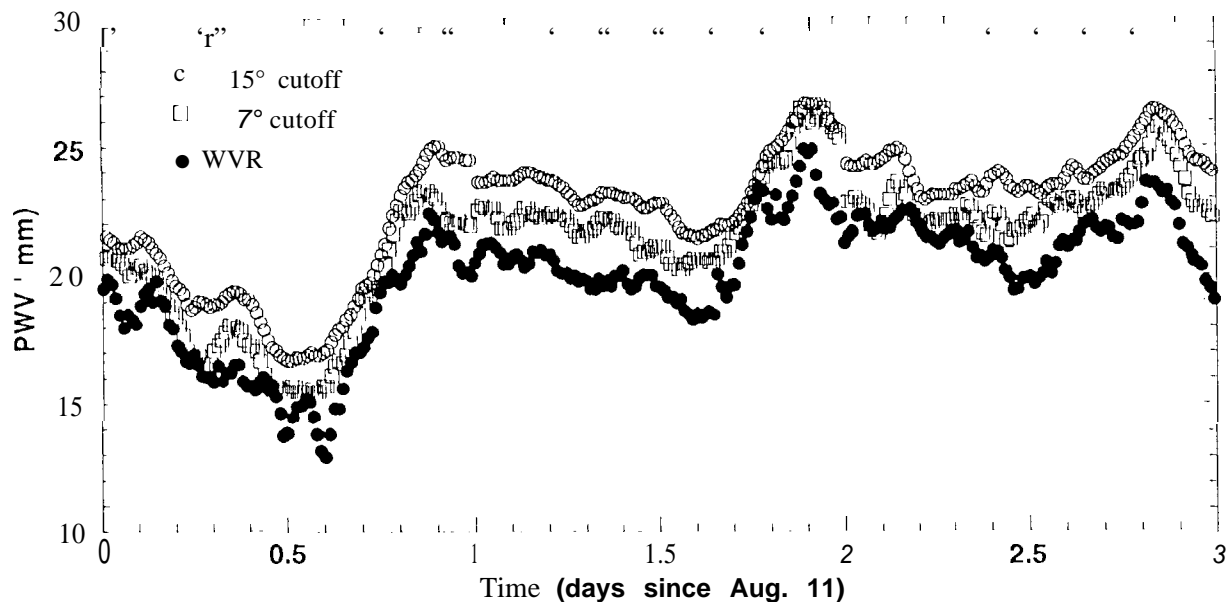[c] Average PWV for this period: 12.66 mm.

Figure 1. Comparison of precipitable water vapor measurements obtained from GPS data and water vapor radiometer data. The 3 days of measurements shown here illustrate the effect of different elevation angle cutoffs when processing the GPS data to estimate precipitable water vapor. The results obtained using a 7° elevation angle cutoff exhibited smaller differences with the WVR results.

observations at elevation angles below 10°. This must be balanced against the deleterious effects of increased multipath noise that may accompany observations at the lower elevation angles.

When considering the results shown in Table 1, it must be remembered that there are inherent limitations to the accuracy of both WVR and GPS-based estimates of PWV. An analysis of major error sources (Runge,]99S), has estimated the uncertainty in GPS-based estimates of PWV to be 1.0-1.4 mm for PWV values in the range of 5-50 mm. Similarly, due to uncertainties in instrument calibrations and retrieval algorithms, the accuracy of WVR measurements of PWV is currently limited to 0.6-2.6 mm. Hence, the close agreement between the PWV estimates for the two techniques during the October comparison period is probably fortuitous and does not reflect the true accuracy of the GPS-based PWV estimates. Furthermore, this intercomparison was carried out in a relatively dry environment. A similar comparison in a more humid area might show larger differences between the two techniques. Nevertheless, these initial results are very encouraging for future development of a GPS-based system for PWV estimation.

Based upon the results of these tests, we make the following recommendations for GPS-based estimation of precipitable water vapor:

- Pressure sensor should be accurate to 0.5 mbar (0.2 mm PWV) or better.

- Temperature sensor should be accurate to 10 C or better.

- observations at low elevation angles (below 10°) should be included to reduce the bias in the PWV estimates.

- Relative heights of the GPS antenna and pressure sensor should be known to about 1 m.

NEAR REAL TIME GPS-BASED ESTIMATES OF PWV

To serve as useful input to numerical weather prediction models, the GPS-based estimates of PWV most be available within a few hours after the data have been recorded. The GPS-based PWV estimates described in the previous section required the use of precise GPS orbits obtained by processing data from a global network of ~30 GPS receivers. Because of the time required to collect and process the data used to provide these precise orbits, it is not practical to use them as the basis for a GPS-based system capable of providing near real time PWV estimates. For this reason, we have investigated the use of "predicted" GPS orbits as an alternative to the precise orbits used in the WVR intercomparison.

The predicted GPS orbits used in this study were obtained by using the equations of motion to map the precise orbits forward in time. Hence, by using predicted GPS orbits, it is possible to process the data from a GPS receiver/meteorological sensor package as soon as they arrive at the central processing facility. The resulting PWV

estimates could be made available shortly after receiving the data,

Because it is not possible to model perfectly all of the forces that affect the orbits of the GPS satellites, the error in the predicted orbits grows as the length of the prediction period increases. This degradation in the orbit accuracy directly translates into reduced PWV accuracy, Furthermore, since the predicted orbits do not contain information on the satellite clocks, it is necessary to difference the data from at least two GPS receivers in order to remove the effects of the satellite clocks, and allow useful 1'WV estimates to be made.[1] Despite these added difficulties, the use of predicted orbits currently offers the most viable means of obtaining G} 'S- based estimates of I'WV in near real time.

With the 1'WV estimates obtained with precise orbits serving as a truth model, we evaluate the accuracy of GPS-based estimates of I'WV obtained using predicted or-bits. Several strategies for PWV estimation with predicted orbits are tested and the results compared to the truth model. Based upon these results, a number of recommendations regarding the use of predicted orbits for 1'WV estimation are presented,

The elements of the PWV estimation process that are investigated include the effects of:

- Station sepal-ation on the accuracy of the estimated I'WV values.

- The time span of the GPS data used to estimate PWV values.

- The length of the GPS orbit prediction period.

- The number of sites used when estimating PWV val-Ucs.

RESULTS OF TESTS USING PREDICTED ORBITS FOR PWV ESTIMATION

All results presented in this section were obtained from GPS and surface meteorological data recorded during the month of October 1995. To remove the e. ffects of satellite clocks, it was necessary to form differenced GPS observations between two or more sites before estimating PWV values at the JPL site. In addition to the total zenith troposphere delays, receiver clocks and site positions were also estimated. in the case of receiver clocks, one site was chosen to serve as the "reference" clock and its clock was not estimated.

Figure 2 shows the effects of changing tbc site separation on the accuracy of the estimated PWV values. The degradation i n I'WV accuracy with decreasing site separa -

tion is probably clue to increasing correlation between the zenith troposphere parameters at the two sites. The site separation must not be too great, however, since mutual visibility of the GPS satellites is required to allow removal of clock effects by differencing the GPS observations.
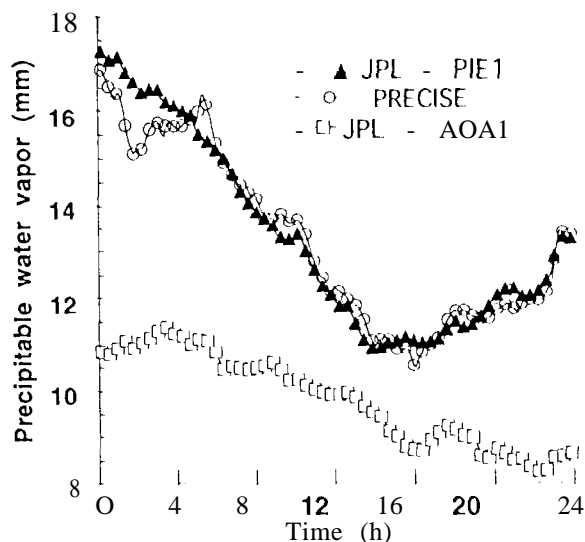

Figure 2 The effect of site separation on the accuracy of GPS-based PWV estimates. The JPL-PIE1 distance is 925 km while the JPL-AOA1 distance is 61 km. 'f 'he "precise" results arc those obtained using post-processed orbits rather than predicted orbits.

The effect of changing the data span is shown in Fig. 3. This figure shows estimates of PWV using data from the JPL and Pietown, NM sites for data spans of 24 h and 3 h. This figure clearly shows that PWV accuracy is degraded with shorter data spans. lo an operational system, however, the time span of the data could be maintained at a fixed value (e. g. 6-12 h). As new GPS observations arrived, they would be appended to the existing data file for the site and older data would be removed. Such a scheme would effectively prevent any degradation in accuracy dLrc to a shortened data span.

It is also possible to usc arbitrarily short data spans without any degradation in accuracy by including the Kalman filter covariance information from earlier processing. This technique would improve the. efficiency of a near real time system by requiring that only the most recent (small) batch of new data be processed as they arrive. This would only involve some additional bookkeeping to keep track of covariance information from earlier filter runs.

Another parameter that can affect PWV accLrracy is the length of the orbit prediction period: the interval between the time that orbits were last estimated and the time that PWV estimates arc made. Because of deficiencies in
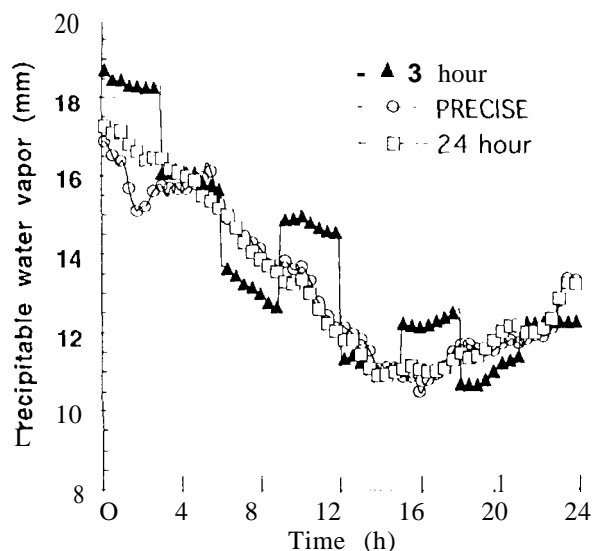
Figure 3 The effect of decreasing the span of the data on the accuracy of G1'S-based estimates of PWV. These results were obtained from data recorded at the JP1, and Pietown, NM sites.

the. physical models that are used to map the estimated orbits forward in time, the accuracy of the predicted orbits degrades in a quadratic fashion as the prediction interval increases. For the orbits used in this study, the orbital accuracy (in three components) degraded from -0.30 m to -2.5 m for a prediction period of 48 hours. Since the orbits are fixed when PWV values are estimated, any degradation in the accuracy of the predicted orbits will
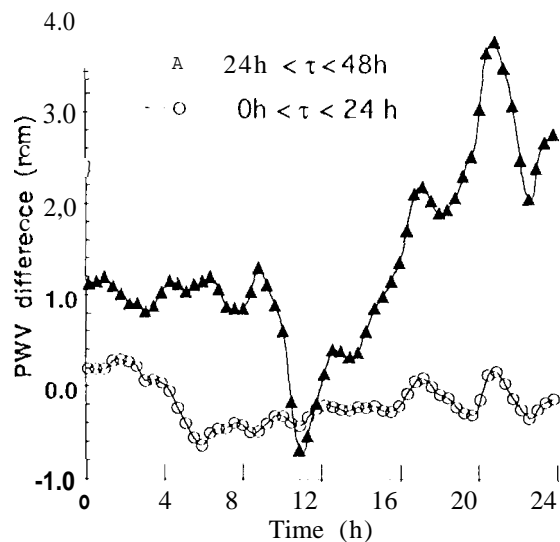

Figure 4 The effect of the orbital prediction period, τ, on the accuracy of the PWV estimates. The quantity plotted on the vertical axis is the difference between the PWV estimates obtained using precise orbits and those obtained using predicted orbits. The data used for this plot were recorded at the JP1, and Pietown sites on Ott. 20, 1995.

directly affect the accuracy of the PWV estimates. The effect of increasing the prediction period is shown graphically in Figure 4. It is clear from this figure that extending the prediction period past one day can result in a significant degradation of PWV accuracy.

If data from more than two sites are available, then it is possible to adjust the orbits in the PWV estimation process. This should improve the. accuracy of the. PWV estimates and alleviate somewhat the effects of an extended prediction period. Figure 5 compares PWV estimates obtained from a two-station case with those obtained using data from three sites, In the three-station case, the predicted orbits were adjusted as part of the PWV estimation process.
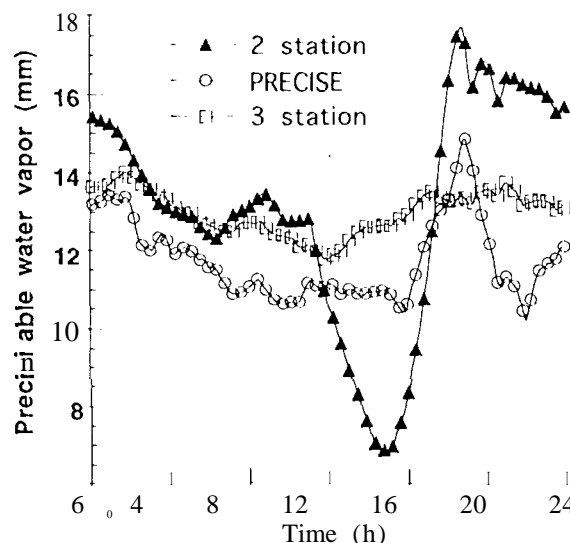

Figure 5 The effect of adding data from a third GPS receiver on the accuracy of PWV estimates. The two-station case used data from J}'], (JPLM) and Pietown (} '11 1). The three-station case added data from a site near Parkfield, CA (1 .EX1). GPS orbits were adjusted in the three-station case.

As a result of these and other studies, we have formulated the following recommendations regarding the use of predicted GPS orbits for estimation of PWV values:

* Site separation must be large enough to eliminate the effects of correlations between the zenith troposphere parameters, but small enough to allow differencing of observations to remove satellite clock effects.

* The data used for PWV estimation should span at least 3 hours or covariance information from previous estimates should be used.

* The prediction period for the orbits should be minimized to prevent degradation in the PWV accuracy due to orbit errors,

- Using data from more than two sites allows the predicted orbits to be adjusted, resulting in more accurate PWV estimates.

- It' orbits are not adjusted, the receiver position should be estimated along with the total zenith delay.[2]

These are in addition to the instrumental accuracy requirements discussed earlier in the section describing comparisons with WVR measurements.

SUMMARY

In this paper we have presented the requirements for a ground-based system for measurement of precipitable water vapor in near real time using (he Global Positioning System. The system described here relies on the use of predicted GPS orbits to allow near real time estimation of PWV values from GPS and surface meteorological data. Based upon test results presented here, a number of recommendations are made regarding meteorological instrumentation and estimation strategies using predicted GPS orbits.

ACKNOWLEDGMENTS

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[2] If the predicted orbits are not adjusted in the estimation process, the orbit errors may propagate into errors in the estimated total zenith delays. Based upon tests using dots from the JPL site, estimation of the GPS site location appears to alleviate this problem and result in more accurate estimates of PWV.